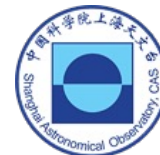


北京师范大学物理与天文学院

SCHOOL OF PHYSICS AND ASTRONOMY, BEIJING NORMAL UNIVERSITY



中国科学院上海天文台

Shanghai Astronomical Observatory, Chinese Academy of Sciences

Constraints on Ultralight Scalar and Dark Photon Dark Matter from PPTA-DR3 and EPTA-DR2

[arXiv: 2605.02172, PRD]

Speaker: Xiao-Song Hu(胡小松)

2nd-year PhD student

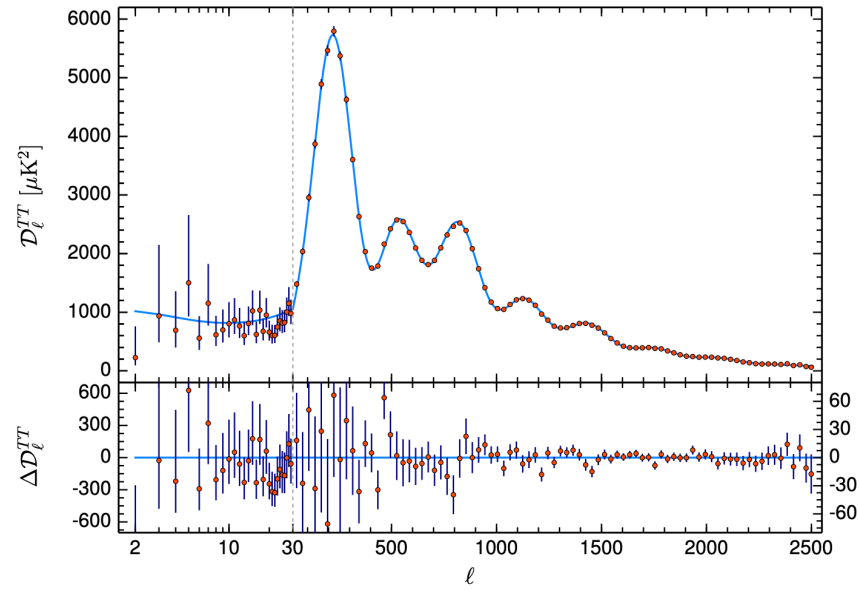
Advisors: Xingjiang Zhu (朱兴江), Kuo Liu (刘阔), Siyuan Chen (陈思源)

Beijing Normal University

Shanghai Astronomical Observatory

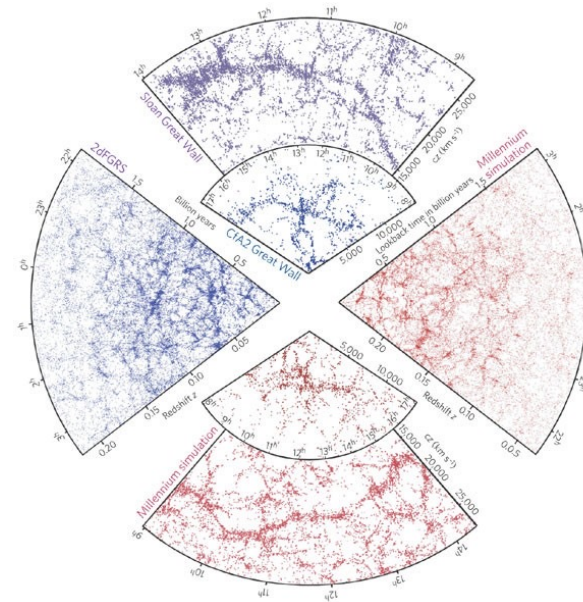
Λ CDM Success on large scales

CMB Anisotropy: The Seeds



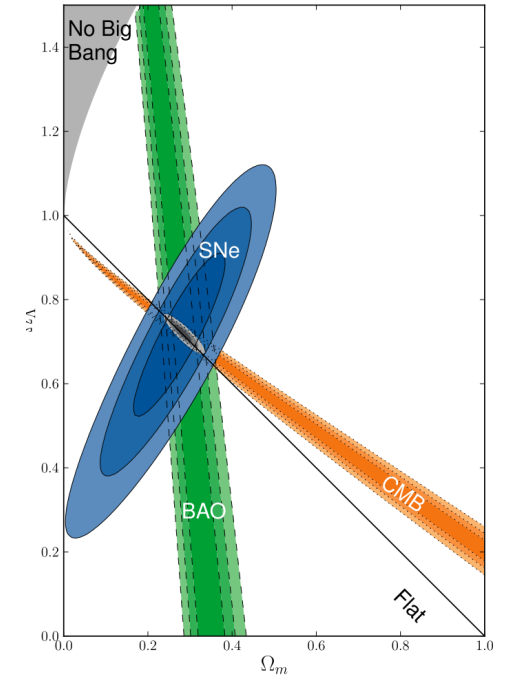
Planck Collaboration (2018)

Large-Scale Structure: The Growth



Springel, Frenk and White (2006)

Supernovae: The Acceleration



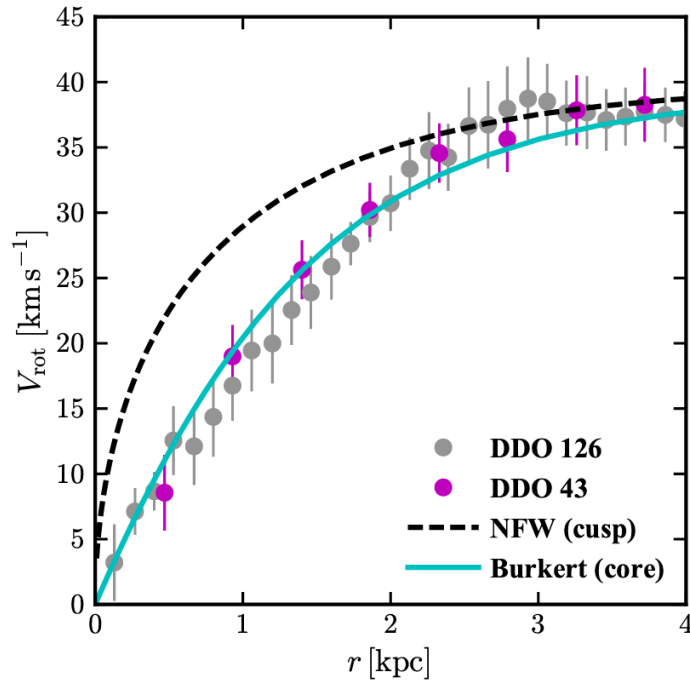
Supernova Cosmology Project (2011)

Λ CDM successfully describes the Universe on large scales.

Small-scale challenge to Λ CDM

Observations in astronomy challenge small-scale predictions of dark matter

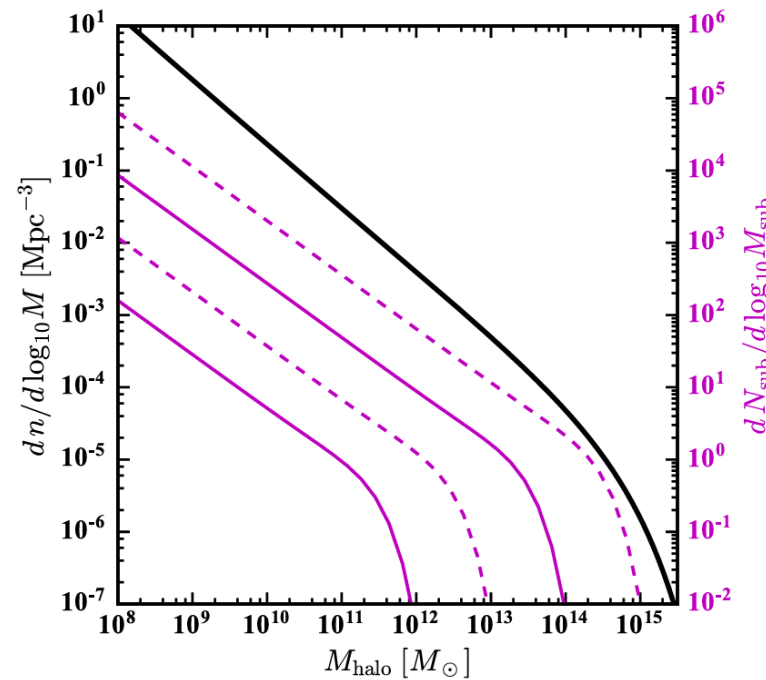
cuspcore problem



Oh et al. (2015)

More cusp density profiles
predicted than observed

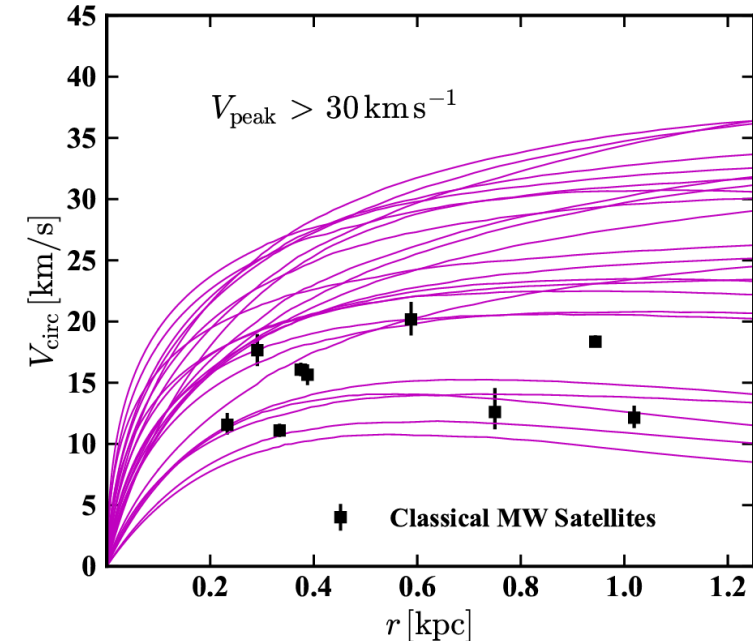
missing satellites



Sheth, Mo and Tormen (2001)

More galactic satellites
predicted than observed

too big to fail



Boylan-Kolchin, Bullock and Kaplinghat (2012)

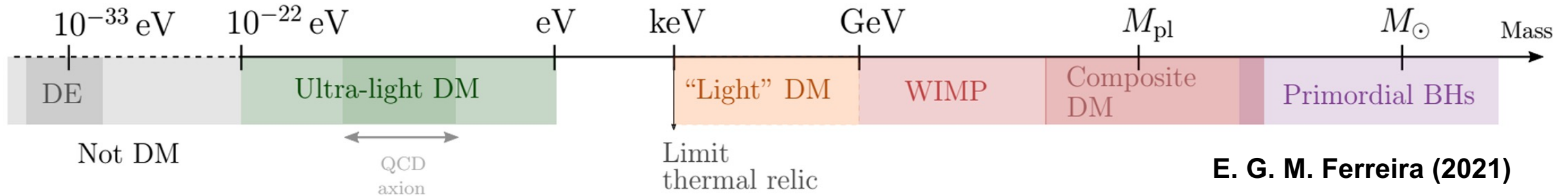
Most massive satellites
predicted denser than observed

Solution of small-scale problem: ULDM

Ultralight dark matter

Ultralight (fuzzy) dark matter

Eg: axion, axion-like particles, dilaton, and dark photon...



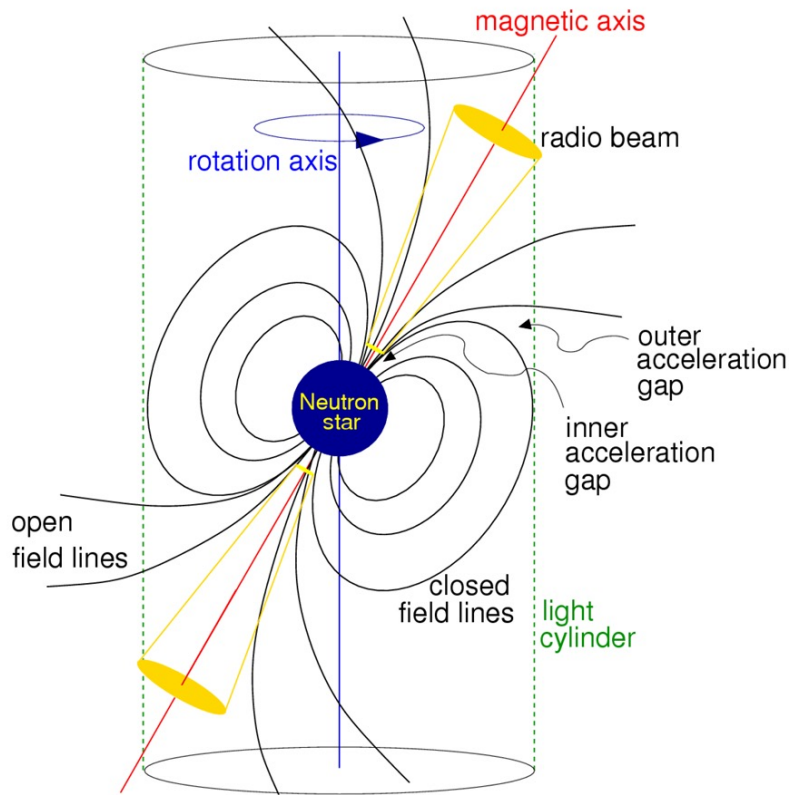
Form Bose-Einstein condensation and **serve as cold dark matter**

mass $\sim 10^{-22}$ eV, oscillation period ~ 1 yr, long de Broglie wavelength ~ 0.5 kpc
(**wave-like behavior**)

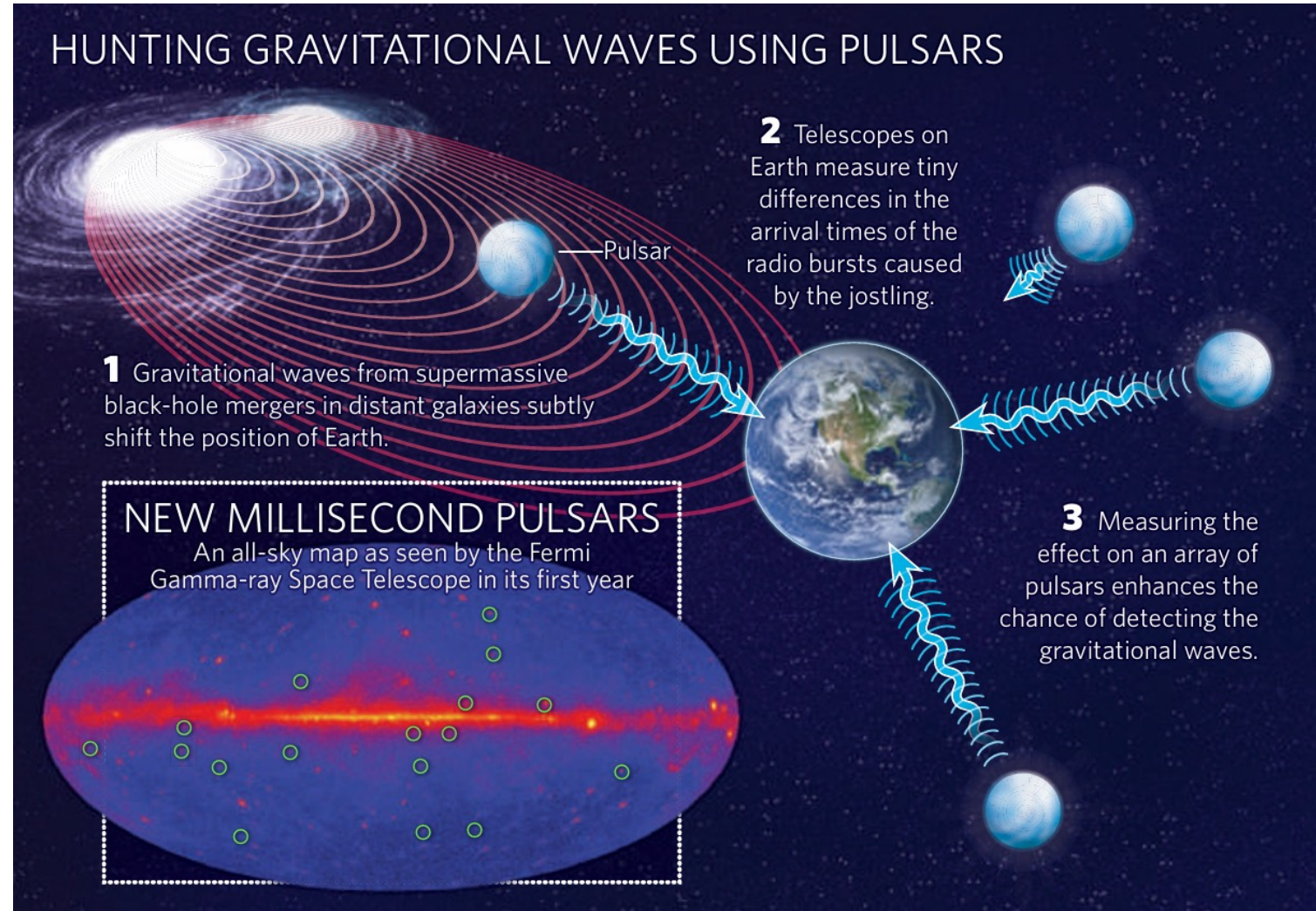
Pulsar timing arrays

Galactic timing interferometer to detect $\sim$ nHz gravitational waves

Millisecond pulsar:
Stable clocks in the Universe
hundreds of times per second

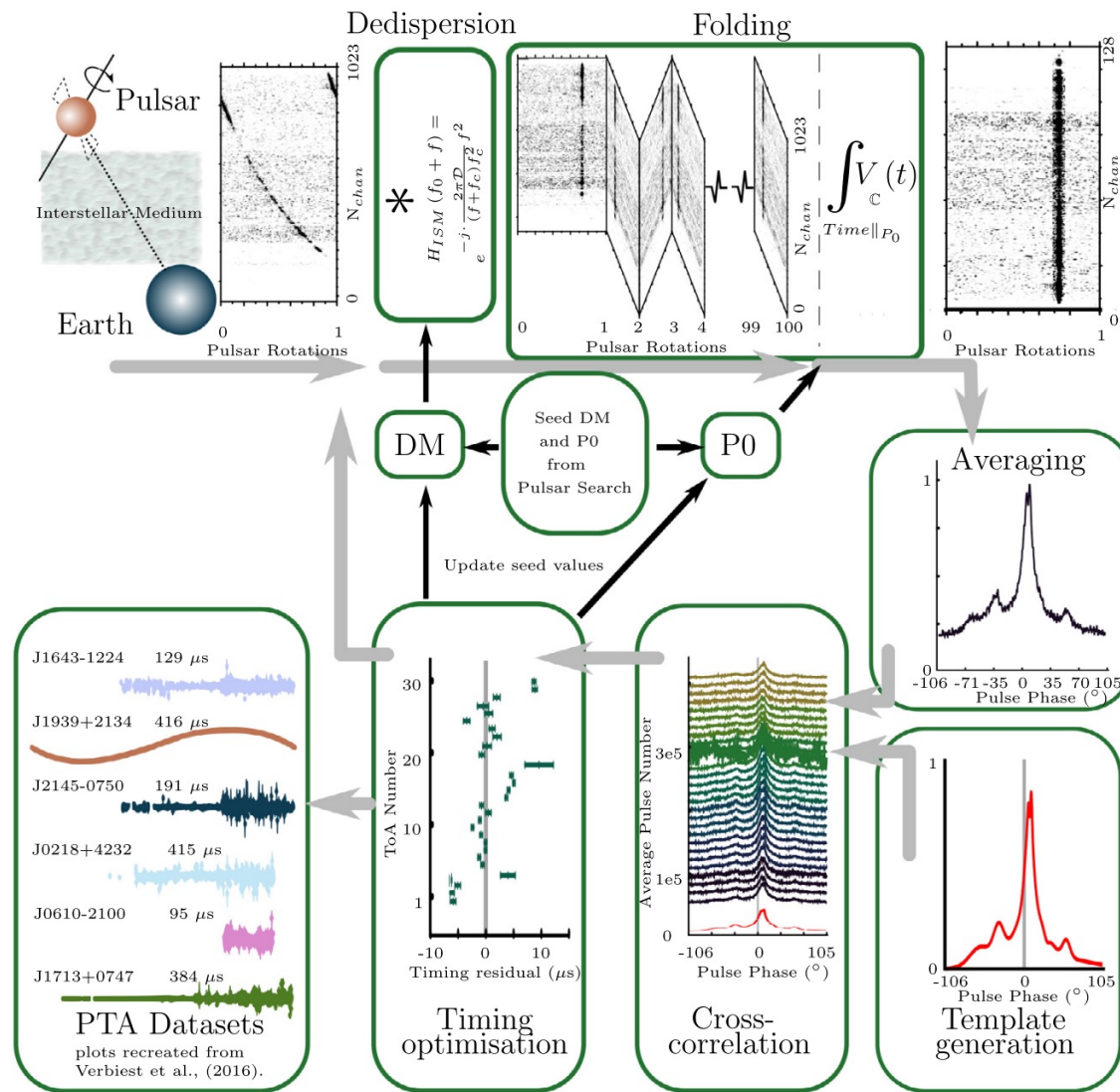


Lorimer and Kramer (2012)

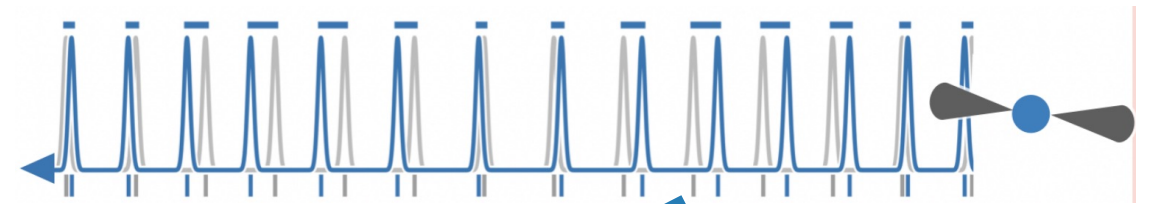


Fermi-LAT

Pulsar timing arrays



Joris et al, 2018



TOAs = **Signal**
Timing model
White Noise
Red noise
DM
.... noise
GWB

ULDM : Model as a deterministic signal

How to detect ULDM?

ULDM Oscillations: Oscillation induce fluctuations in the spacetime metric.

The oscillating ULDM field perturbs the gravitational potential, leading to observable variations in the TOAs.

$$\Delta t = \frac{\Psi}{2m} \left[\widehat{\phi}_e^2 \sin(2mt + \alpha_e) - \delta\rho_{\text{DM}} \widehat{\phi}_p^2 \sin(2mt + \alpha_p) \right]$$

ULDM Interaction: Interaction with Standard Model particles.

ULDM direct interaction with Earth and Pulsars, produce additional modifications in the TOAs through a distinct mechanism

$$\Delta t_{\text{DPDM}} = \frac{\epsilon e}{m} A_0 \left[\widehat{\phi}_e \frac{q_e}{m_e} \cos(mt + \alpha_e) - \sqrt{\delta\rho_{\text{DM}}} \widehat{\phi}_p \frac{q_p}{m_p} \cos(mt + \alpha_p) \right] n$$

This two principal mechanisms generate measurable changes in TOAs.

Parkes Pulsar Timing Array constraints on ultralight scalar-field dark matter

Nataliya K. Porayko,^{1,*} Xingjiang Zhu,^{2,3,4,†} Yuri Levin,^{5,6,2} Lam Hui,⁵ George Hobbs,⁷ Aleksandra Grudskaya,⁸ Konstantin Postnov,^{8,9} Matthew Bailes,^{10,4} N. D. Ramesh Bhat,¹¹ William Coles,¹² Shi Dai,⁷ James Dempsey,¹³ Michael J. Keith,¹⁴ Matthew Kerr,¹⁵ Michael Kramer,^{1,14} Paul D. Lasky,^{2,4} Richard N. Manchester,⁷ Stefan Osłowski,¹⁰ Aditya Parthasarathy,¹⁰ Vikram Ravi,¹⁶ Daniel J. Reardon,^{10,4} Pablo A. Rosado,¹⁰ Christopher J. Russell,¹⁷ Ryan M. Shannon,^{10,4} Renée Spiewak,¹⁰ Willem van Straten,¹⁸ Lawrence Toomey,⁷ Jingbo Wang,¹⁹ Lingling Wen,^{3,4} and Xiaopeng You²⁰

(PPTA Collaboration)

There are a couple of ways to improve our analysis. First, the coherence between pulsar terms and Earth terms can be used to enhance the sensitivity. When a pulsar and the Earth are located within a de Broglie wavelength λ_{dB} , the oscillation phases, which have been assumed to be independent in the current analysis, are correlated. However, for $m \gtrsim 10^{-22}$ eV, this effect will have no impact on the current results, since $\lambda_{\text{dB}} = 60 \text{ pc}(10^{-22} \text{ eV}/m)$ and no pulsars have been found within 60 pc to the Earth. Another interesting point is that pulsars that are close to each other within λ_{dB} also experience phase-coherent oscillations [36]. We plan to explore these features in a future work.

Second, the oscillation amplitude Ψ_c is proportional to the local dark matter density. Thus, in contrast to the amplitude of the Earth term, the amplitude of the pulsar term varies from pulsar to pulsar; see Eq. (7). In Λ -FDM cosmological simulations [29,36], it was shown that due to wave interference the dark matter forms gritty pattern with typical granule size of around λ_{dB} . When averaged over $\gg \lambda_{\text{dB}}$ scales, the periphery ($> 1 \text{ kpc}$) density profile is similar to the classical Navarro-Frenk-White (NFW) profile, whereas a distinct density peak is seen in the central regions (usually called solitonic core, see [29] for details).

First: The Pattern of Interference is determined by the ULDM Coherence Length.

$$l_c = \frac{2\pi}{mv} \approx 0.4 \text{ kpc} \left(\frac{m}{10^{-22} \text{ eV}} \right)^{-1}$$

For simplicity, we consider two cases: $\hat{\phi}_e$ and $\hat{\phi}_p$

Uncorrelated: Coherence Length small than Pulsar-Earth Separation

Correlated: Coherence Length large than Pulsar-Earth Separation

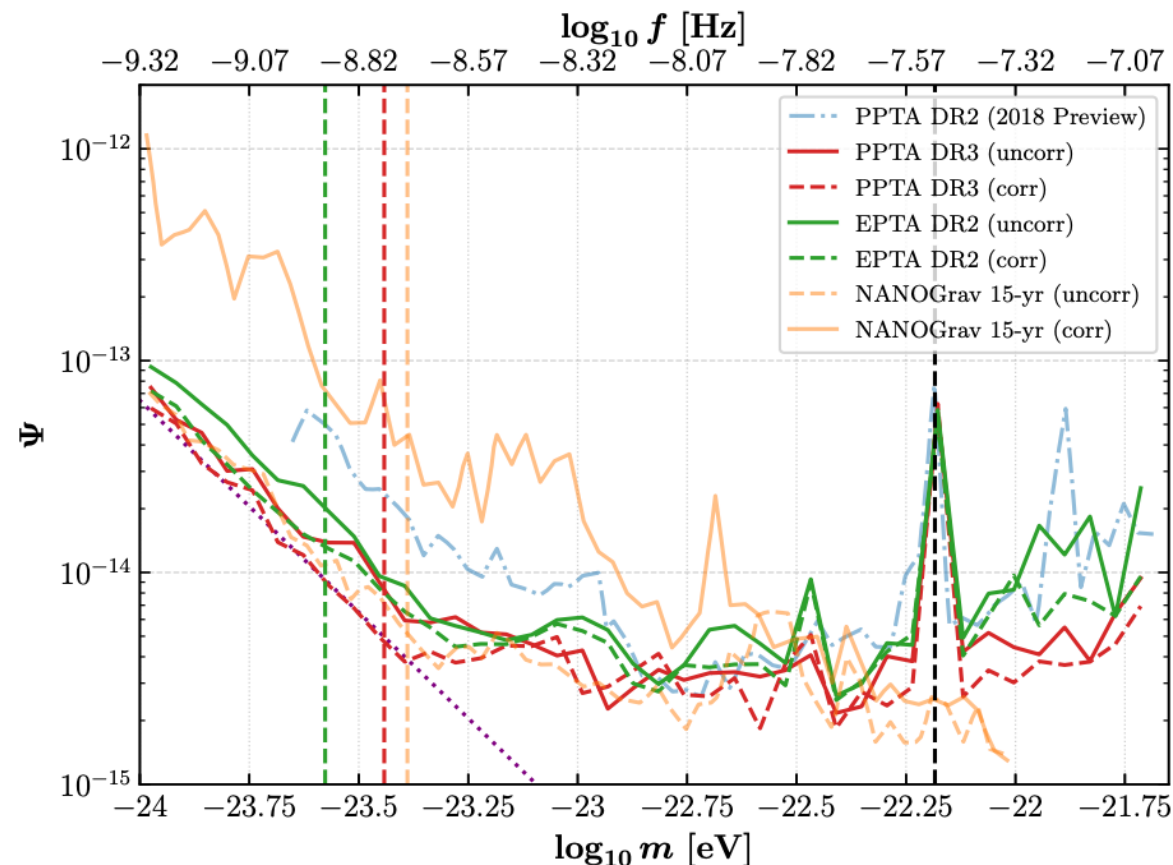
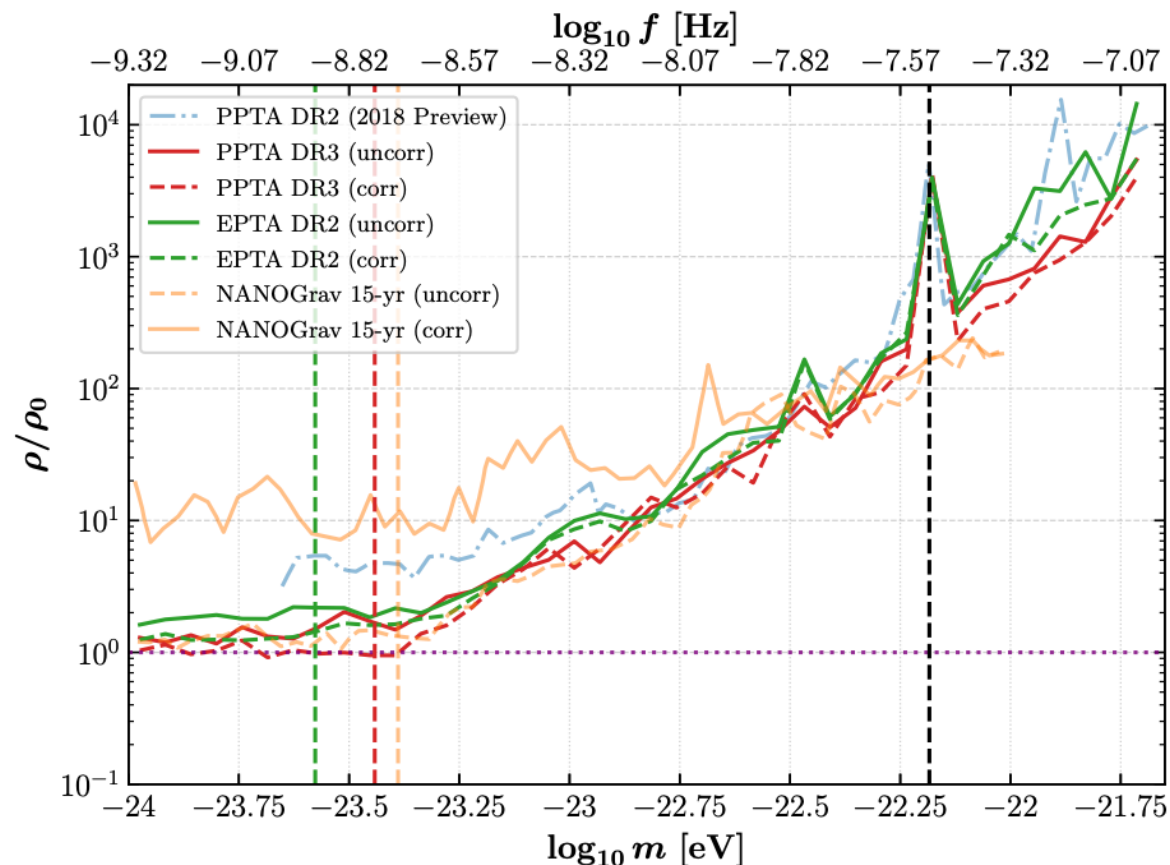
Second: The dark matter density in the Earth term and the Pulsar term is different.

$$\delta\rho_{\text{DM}} = \frac{\rho(x_p)}{\rho(x_e)}$$

We define a dark matter density ratio between pulsars and Earth to set a common amplitude.

Results

Upper limits on scalar ULDM (PPTA-DR3 and EPTA-DR2):



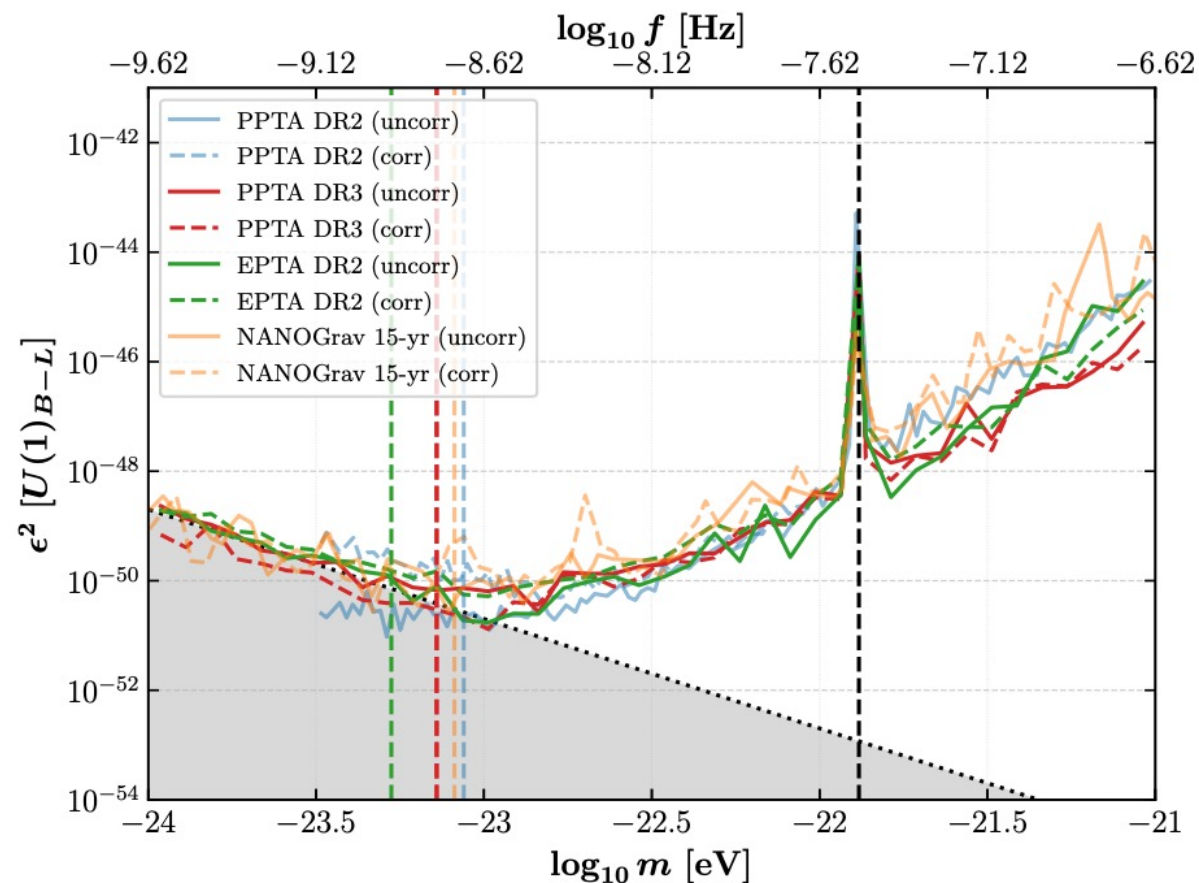
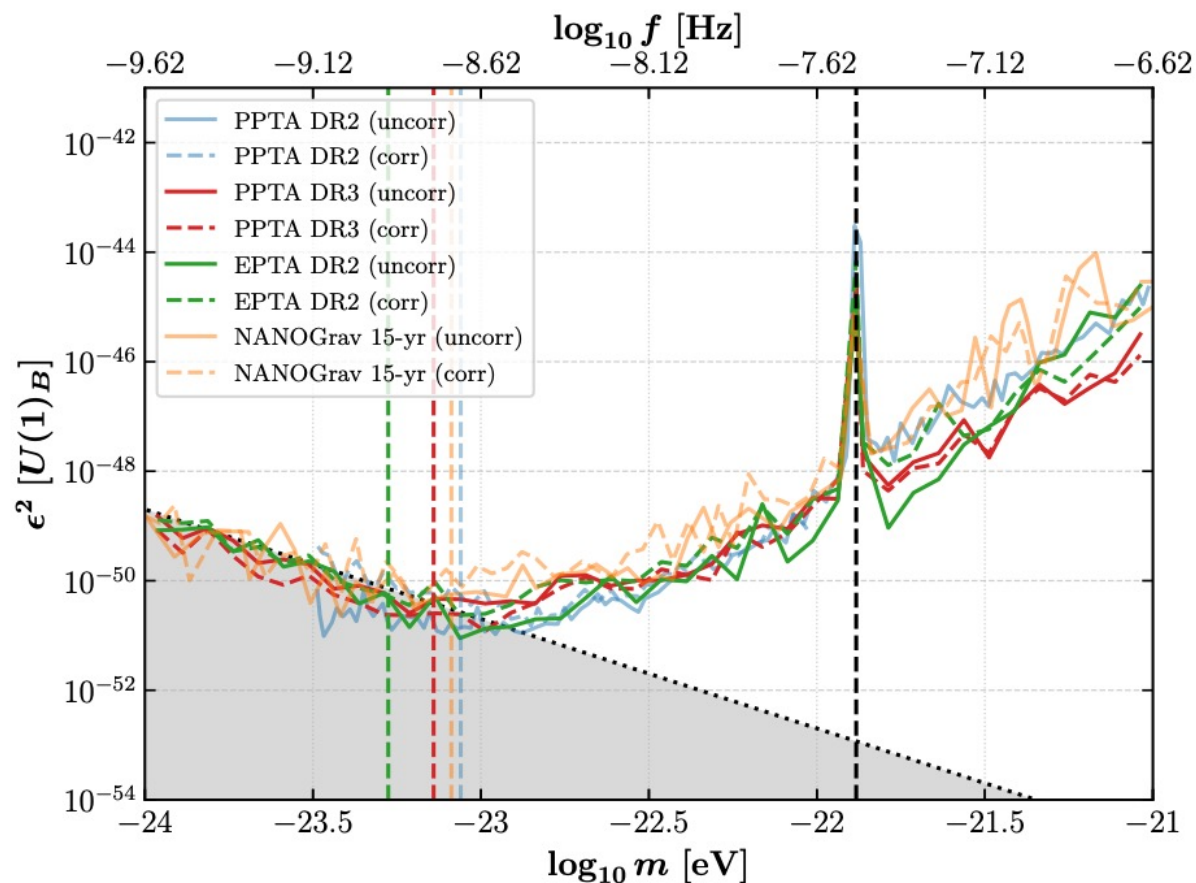
Purple dot line: the local dark matter density 0.4 GeV/cm^3

Vertical dashed lines mark the approximate observational timespan.

Black is one year reference peak.

Results

Upper limits on DPDM (PPTA-DR3 and EPTA-DR2):



The black dotted line and gray shaded region indicate the parameter space where gravitational effects dominate over fifth-force couplings, based on the simplified assumption that vector ULDM produces gravitational oscillations three times stronger than scalar ULDM.

Summary

- 1. We search for ULDM using PTAs, the gravitational signal of scalar ULDM and the fifth-force signal from DPDM.**
- 2. We compute the dark matter density ratio between Earth and the pulsar, which in turn sets a common amplitude for the signal.**
- 3. For scalar ULDM, our analysis does not exclude the scenario in which ULDM constitutes all of dark matter.**
- 4. For the DPDM, the results are compared to previous results.**

Thanks!